Final Report on "Cellular Decomposition Based Hybrid-Hierarchical Control Systems with Applications to Flight Management Systems"
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Summary Report of Research Performed under NASA Grant # NAG 2-1040

Overview

The work in this research project has been focused on the construction of a hierarchical hybrid control theory which is applicable to flight management systems. The motivation and underlying philosophical position for this work has been that the scale, inherent complexity and the large number of agents (aircraft) involved in an air traffic system imply that a hierarchical modelling and control methodology is required for its management and real time control. In the current work the complex discrete or continuous state space of a system with a small number of agents is aggregated in such a way that discrete (finite state machine or supervisory automaton) controlled dynamics are abstracted from the system's behaviour. High level control may then be either directly applied at this abstracted level, or, if this is in itself of significant complexity, further layers of abstractions may be created to produce a system with an acceptable degree of complexity at each level. By the nature of this construction, high level commands are necessarily realizable at lower levels in the system.

Current work is concentrating on the extension of the research summarized here to cases where many agents and, in addition, various disturbances, enter the dynamics of the base level system.

Brief Description of Results

The results which have been obtained fall into the six main groups below.

Discrete Hierarchical Control Theory: Finite State Machines

The notion of Dynamical Consistency (DC) as a key idea for the aggregation of the dynamics of control systems first appeared in the 1995 *Systems and Control Letters (SCL 1995)* paper of PEC and Y. J. Wei and was reported by them at the IFAC Congress of 1996. (See the publications list below for this other references to published work.) The principle notion is that, once any partition of the state space of controlled system has been chosen, a high level (i.e. abstract) controlled transition between any two blocks

is defined when all the states in the first of the two blocks can be driven (without detours into other blocks) through the first block into the second. The control sequence may differ for different initial states in the first block. Furthermore, a hierarchical lattice structure is shown to exist which permits the specification of hierarchical control systems for the original base system. One of the principal results of this theory is that subject to the condition that all blocks are controllable with respect to themselves (in-block controllability (IBC)), the base machine is controllable if and only if the partition machine is controllable. In other words, high and low level controllability are equivalent subject to the IBC condition.

For systems with identified start and terminus state sets, the ideas above were generalized by PEC, Gupta and Shen so as to apply to complex systems where controllability only needs to be defined with respect to these distinguished states sets. (See *SCL, 1997; CDC, 1997a*. See also *AIRTC 1998*).

Supervisory Control

Somewhat remarkably, these notions extend in a direct and comprehensible manner to the controlled automata of Supervisory Control Theory; here control is exercised by disabling the so-called controllable events and control is conducted so as to prevent the uncontrollable events giving rise to unacceptable behaviour. In the papers of Hubbard, Shen and PEC (*CDC 1997b*) and Hubbard and PEC (*WODES, 1998, CDC, 1998b*) this development is presented in detail and applications to transfer lines are given. A key feature of the supervisory control framework (at any level of aggregation) is that it has an immediate interpretation as disturbance rejection theory.

Hierarchically Accelerated Dynamic Programming (HADP)

In the context of this research program and that of the air traffic control problem, we observed that the level by level construction of the partition machines permitted the introduction of a hierarchical version (HADP) of standard Dynamic Programming (DP). As described by Shen and PEC in *CDC 1998c*, enormous accelerations (of up to two or three orders of magnitude) of solution of standard DP shortest path algorithms are made possible

by the use of HADP. Estimates of the suboptimality of the resulting solutions are given by the current theory (see *CDC 1998c*). Work continues to improve the results in this direction and to design more general and flexible software (*IFAC, 1999b*).

Hierarchical Hybrid Control of Differential Control Systems

Y.J. Wei and PEC (see *Block 1996; IFAC, 1996; Ithaca, 1996; Lushan, 1997; IEEE AC 1998*) extended the theory of hierarchical control based upon the construction of the DC partition machines to the case where the base machine is a differentiable control system. Despite the increase in the technicality of the construction, the strategy is conceptually parallel to the discrete base system case; it results in the abstraction of continuous base system dynamics into discrete higher level abstractions.

Nonlinear Global Controllability with Application to the Construction of Hybrid In-Block Controllable (HIBC) Partition Machines

The work above has been deepened and extended in the work of Lemch and PEC in the following ways: the crucial question of the robustness, or stability, of the abstracted partition machine (controlled) dynamics with respect to perturbations in the boundaries of the blocks defining the state space partitions is answered in the affirmative in *HSCC '98*. This is subject to the Hybrid In-Block Controllability Condition (HBC), in addition to some technical conditions.

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The representation of any finite machine by a partition machine of some differential control system was established in *SCL, 1998*.

The importance of the HBC property as a sufficient condition for the realizability of state-to-state controlled trajectories by a combination of high and low level controls, and its significance for the robustness of partition machine specification, led to the development of a general theory of nonlinear controllability which gives the HIBC property as an immediate product whenever the relevant hypotheses apply. This theory is presented by PEC and Lemch in the papers: *HSCC '98; CDC 1998a; CDC 1998d; IFAC, 1999a*. An important feature of this work is that it naturally applies to Hamiltonian

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systems and, further, systems such as the planar aircraft control model (for which first integrals may be shown to exist).

Hybrid Partition Machines

Finally, the work above has been applied in order to construct abstracted models of the "standard" (base level) hybrid system models. This results in discrete (high level) partition machine representations of such conventional hybrid systems and permits the high + low level hierarchical control of such systems in the manner developed above for, respectively, discrete, supervisory and continuous base machines. This work is reported in: *CDC 1998d; IFAC, 1999; AAAI 1999.*

Publications of Work Supported by NASA Grant # NAG 2-1040

Journal and Volume Publications

SCL 1998 Lemch E. and P. E. Caines, "On the Existence of Hybrid Models for Finite State Machines", *Systems and Control Letters*, to appear, 1998.

HSCC '98 Lemch E. and P. E. Caines, "Hierarchical Hybrid Systems; Partition Deformations and Applications to the Acrobot System". Proceedings of the *First International Workshop on Hybrid Systems: Computation and Control, HSCC '98, U. C. Berkeley, CA, April 13-15, 1998. Lecture Notes in Control and Information Sciences 1386, Eds. T. A. Henzinger and S. Sastry*, Springer, NY, 1998, pp. 237-252.

IEEE AC 1998 Caines, P.E. and Wei, Y-J. "Hierarchical Hybrid Control Systems: A Lattice Theoretic Formulation". *IEEE Transactions on Automatic Control Special Issue on Hybrid Systems*, 43, No. 4, April, 1998, pp. 1-8.

SCL 1997 Caines, P.E., V. Gupta and G. Shen, "The Hierarchical Control of ST-Finite State Machines", 32, No.4, *Systems and Control Letters*, 1997, pp. 185-192.

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Block 1996 Caines, P.E. and Wei, Y-J. " Hierarchical Hybrid Control Systems". *Control Using Logic-Based Switching. Proceedings of the Block Island Workshop, October, 1995, Lecture Notes in Control and Information Sciences, 222. Ed. Steve Morse,* Springer Verlag. NY, 1996. pp 39-48.

SCL 1995 Caines, P.E. and Y-J. Wei, "The Hierarchical Lattices of a Finite Machine". *Systems and Control Letters,* 25, 1995, pp. 257-263.

Conference Presentation Published in Refereed Proceedings

AAAI 1999 Caines, P. E. and Lemch, E. S., "Hybrid Partition Machines with Application to Air Traffic Control Systems" To be presented at the *Hybrid Control Session of the AAAI Meeting,* Stanford, March, 1999.

IFAC 1999a Caines, P. E. and Lemch, E. S., " Hierarchical Hybrid Control and the Global Controllability of Hamiltonian and Other Nonlinear Systems". To be presented *World IFAC Congress,* Beijing, PRC, July, 1999.

IFAC 1999b Shen, G. and Caines, P. E., " Hierarchically Accelerated Dynamic Programming with Applications to Transportation". To be presented *World IFAC Congress,* Beijing, PRC, July, 1999.

CDC 1998a Caines, P. E. and Lemch, E. S., " On the global controllability of Hamiltonian and other nonlinear systems: fountains and recurrence", Proc. *37th IEEE Conference on Decision and Control,* Tampa, Florida, 1998.

CDC 1998b Hubbard, P. and Caines, P. E. " Trace-DC hierarchical supervisory control with applications to transfer-lines", Proc. *37th IEEE Conference on Decision and Control,* Tampa, Florida, 1998.

CDC 1998c Shen, G. and Caines, P. E., " Control consistency and hierarchically accelerated dynamic programming", Proc. *37th IEEE Conference on Decision and Control,* Tampa, Florida, 1998.

CDC 1998d Caines, P. E. and Lemch, E. S., "Partition Machines for

Hybrid Systems with Applications to Air Traffic Management Systems" Presented at the *37th IEEE Conference on Decision and Control, 1998* workshop "Hybrid Systems: Modelling, Analysis and Control" .

AIRTC 1998 Caines, P. E., T. Mackling, C. Martinez-Mascarua, "CO-COLOG Logic Control for Hierarchical and Hybrid Systems", Presented at the *7th IFAC International Symposium on Artificial Intelligence in Real Time Control*, Grand Canyon, AZ. USA, October 5 - 8, 1998. IFAC Extended abstract volume: pp 20-22; eds. Y-H Pao and S.R. LeClair. Also available on conference CD-ROM. *Recipient AIRTC'98 Best Paper Award.*

WODES 1998 Hubbard, P. and P. E. Caines, " A state aggregation approach to hierarchical supervisory control with applications to a transfer line example", Proc. of the IEE International Workshop on Discrete Event Systems (WODES), p. 2-6, Cagliari, Sardinia, August 1998.

CDC 1997a Caines P.E., V. Gupta and G. Shen, "The Hierarchical Control of ST-Finite State Machines". *36th. IEEE Conference on Decision and Control*, San Diego, CA, December, 1997, pp 3584-3589.

CDC 1997b Caines P.E., P. Hubbard and G. Shen," State Aggregation and Hierarchical Supervisory Control". *36th. IEEE Conference on Decision and Control*, San Diego, CA, December, 1997, pp 3590-3591.

Lushan 1997 Caines P. E. " Hierarchical Hybrid Control Systems" , Proceedings of the Chinese Control Conference, Lushan, Jiangxi, P. R. China, 17 - 23, August, 1997 pp. 10-20.

Ithaca 1996 Caines P. E. and Y-J. Wei, "Hierarchical Hybrid Systems",presented at the Fourth International Conference on Hybrid Systems, Ithaca, NY, October 12-14, 1996.

IFAC 1996 Caines P.E.and Y-J. Wei, "Hierarchical Control of Hybrid Systems", Preprints of the 13th World Congress of IFAC, San Francisco, CA, July, 1996, Volume E, Nonlinear Systems 1, pp 455-459.